DEVELOPMENT OF A LARGE-AMPLITUDE 500-MB. TROUGH IN WESTERN UNITED STATES AND ASSOCIATED SURFACE CYCLOGENESIS, NOVEMBER 13–18, 1958

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1. INTRODUCTION

During the period from November 13 to 18, 1958, a major upheaval in the zonal index over the United States took place, followed by a relatively rapid change to near normal conditions. This development was responsible for extremes in temperature over southwestern and southeastern United States; heavy snows in the Rocky Mountains and the north and west-central Plains regions; and an intense, rapid cyclogenesis over central United States. A rash of tornadoes and high wind storms occurred from north-central Texas into west-central Illinois on November 17 in intimate association with the cyclogenesis and the advancing cold front.

Some of the vital statistics of the period are shown in figure 1. When considering figure 1, one is immediately impressed with the large area over which the extremes in weather occurred. An interesting point is that the broad features of the upper circulation and the mean position of the major frontal zone during the period can be diagnosed without additional information.

The purpose of this brief article is to describe by use of 1000-mb., 500-mb., and 1000–500-mb. thickness charts

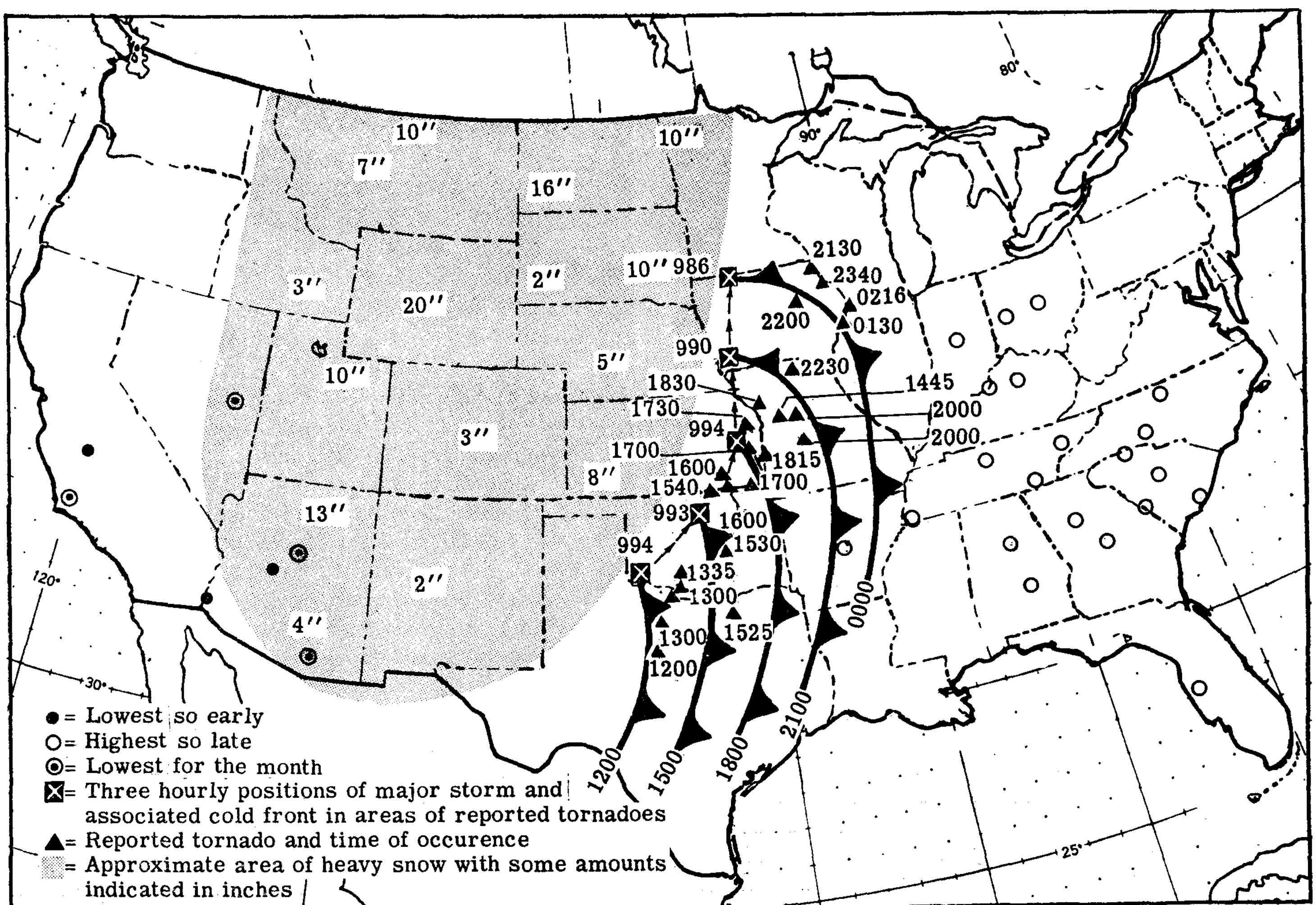


Figure 1.—Extremes in weather that occurred over the United States during the period November 15 to 19, 1958.

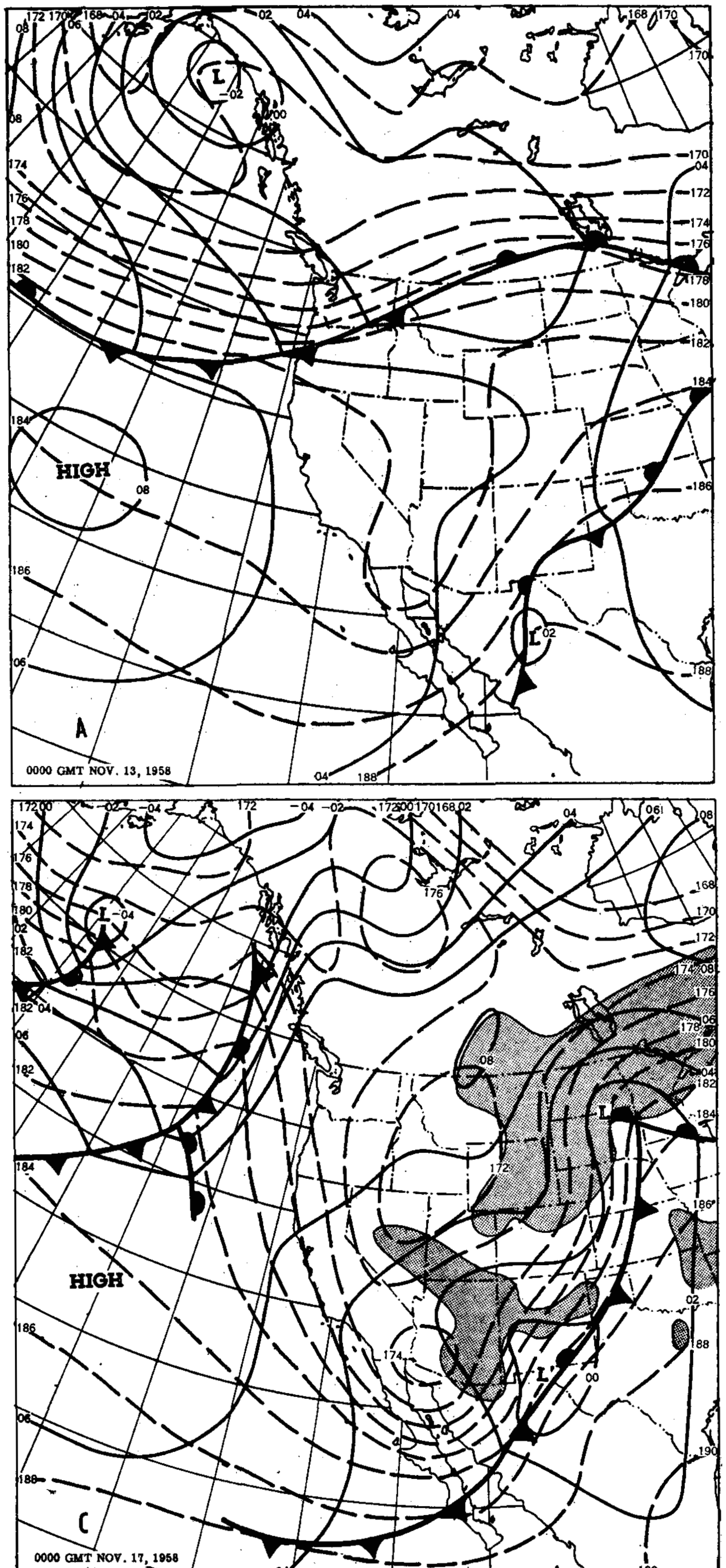


FIGURE 2.—1000-mb. contours (solid lines) and 1000–500-mb. thickness (dashed lines, labeled in hundreds of feet) for period of Stage I, November 13–17, 1958. Shaded areas show current precipitation.

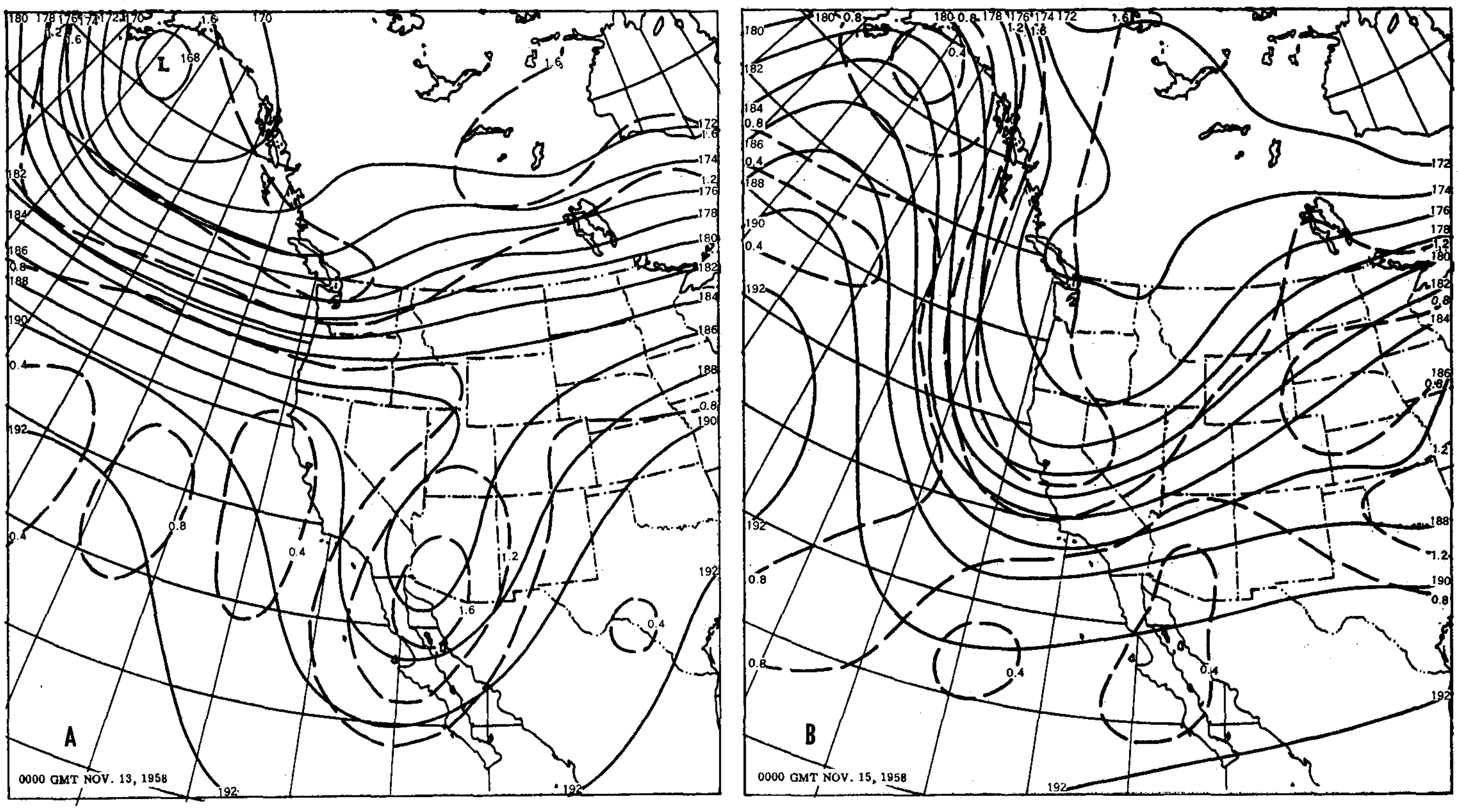
the course of meteorological developments during the period of November 13–18, and, in so doing, to focus attention on some of the salient characteristics. In addition, the usefulness of the operational JNWP 500-mb. barotropic prediction to the forecast problem is explored in view of these characteristics and the Sutcliffe [1] development equation.

For purposes of description and identification of characteristics it is convenient to divide the period into two stages. Stage I includes the period from 0000 GMT, November 13, to 0000 GMT, November 17; Stage II, the period 0000 GMT, November 17, to 1200 GMT, November 18.

2. STAGE I

Figures 2 and 3 show the 1000-mb. and 500-mb. charts, respectively, at 48-hour intervals, beginning with 0000 GMT, November 13. The 1000-mb. charts include 1000–500-mb. thickness contours and the 500-mb. charts isopleths of absolute vorticity. The 500-mb. absolute vorticity was obtained from JNWP computations which make use of a nondivergent stream function obtained from the height field of an objective analysis. The 500-mb. charts presented here are carefully constructed subjective analyses and differ in some respects from the objective analyses. Consequently, there are some inconsistencies between the absolute vorticity isopleths and 500-mb. analyses. However, since the discussion is qualitative in nature, the inconsistencies are not considered important.

At 0000 GMT on November 13 (figs. 2A and 3A) we first note a cold 500-mb. Low and a vorticity maximum centered over the northern Gulf of Alaska just about vertical with their 1000-mb. counterparts. A well-defined frontal zone at both the 1000-mb. and 500-mb.



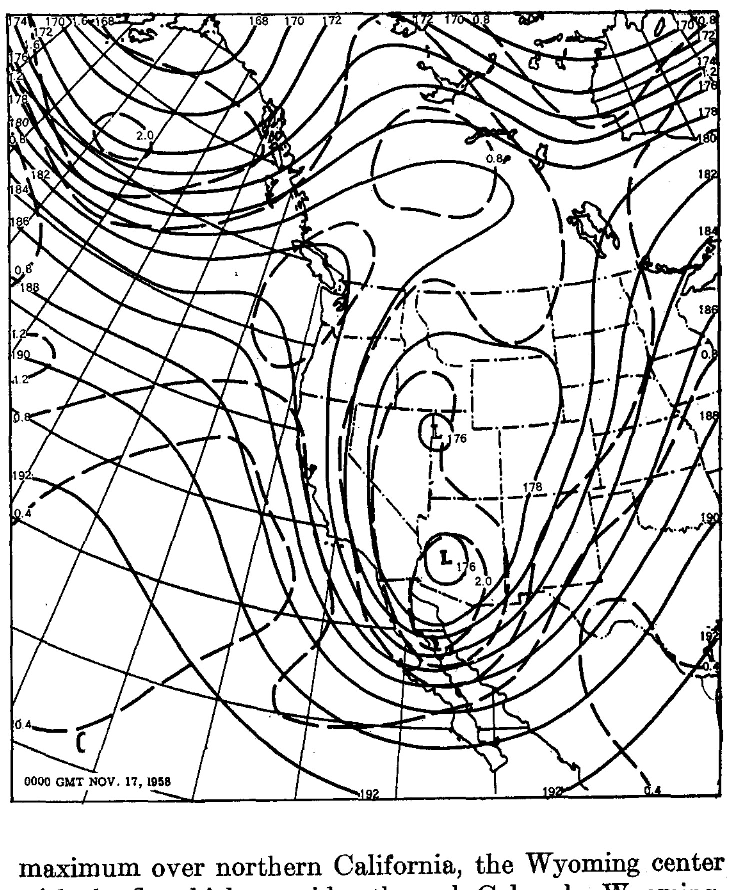
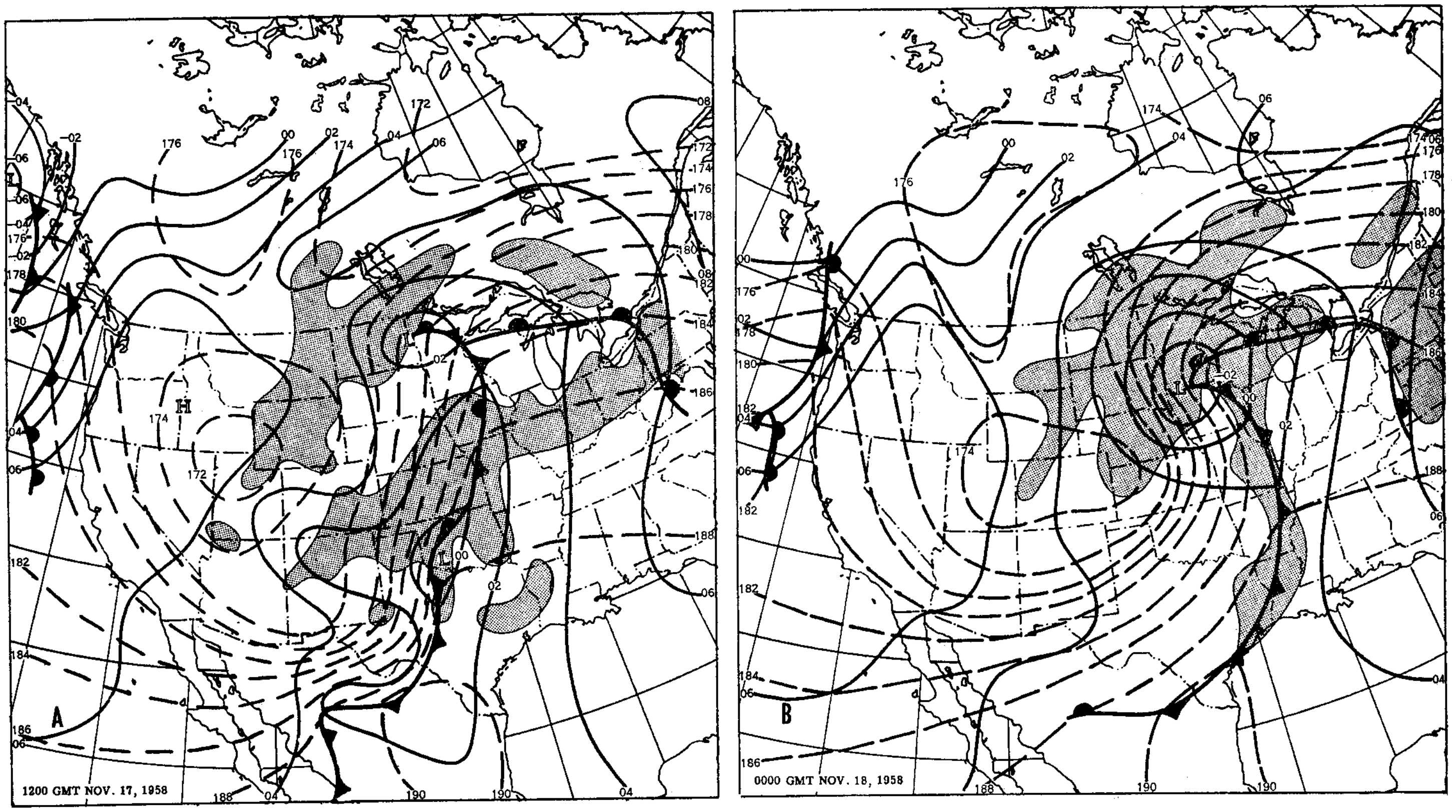


FIGURE 3.—500-mb. contours (solid lines, labeled in hundreds of feet) and absolute vorticity (dashed lines, unit 10^{-4} sec^{-1}) for times corresponding to figure 2.

levels extended in an east-west direction south of the cold Low. A feeble wave was located along the Canadian border north of Montana in association with a vorticity maximum at 500 mb. over Vancouver Island.

In figures 2B and 3B we see how the situation changed during the 48-hour period. There was a remarkable amplification in the 500-mb. circulation over western North America as cold air and vorticity moved from the northern Gulf of Alaska southeastward into the Pacific Coast States and a strengthening ridge moved into the Gulf of Alaska. Despite the amplification of the 500-mb. trough there was little change in absolute vorticity judging from the size of the area enclosed by the 1.6×10^{-4} isopleth. The area of maximum 1000-mb. vorticity also shifted southeastward into the Central Rockies and Central Plateau regions in conformity with the 500-mb. changes. It is noteworthy that even with the amplification of the upper trough, the phase between the 500-mb. contours and thickness contours changed little and there was no 1000-mb. development of consequence. The low-level frontal system moved southeastward into far western United States at an average speed of close to 15 knots, which is in strict concert with the average gradient directed normal to the front during the 48 hours and the movement of the upper trough. Two Low centers were in evidence along the front, one in extreme eastern Nevada and the other in southern Wyoming. The Nevada center was associated with the 500-mb. vorticity maximum over northern California, the Wyoming center with the flat thickness ridge through Colorado, Wyoming, and Montana.

Forty-eight hours later, we see, in figures 2C and 3C, the upper trough had undergone still further amplification and its progression eastward had slowed over the



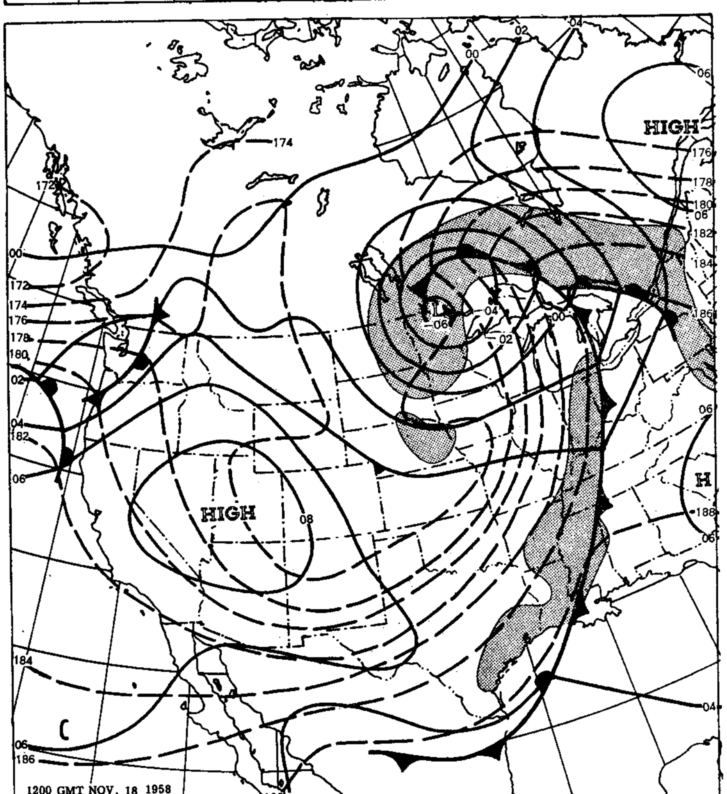
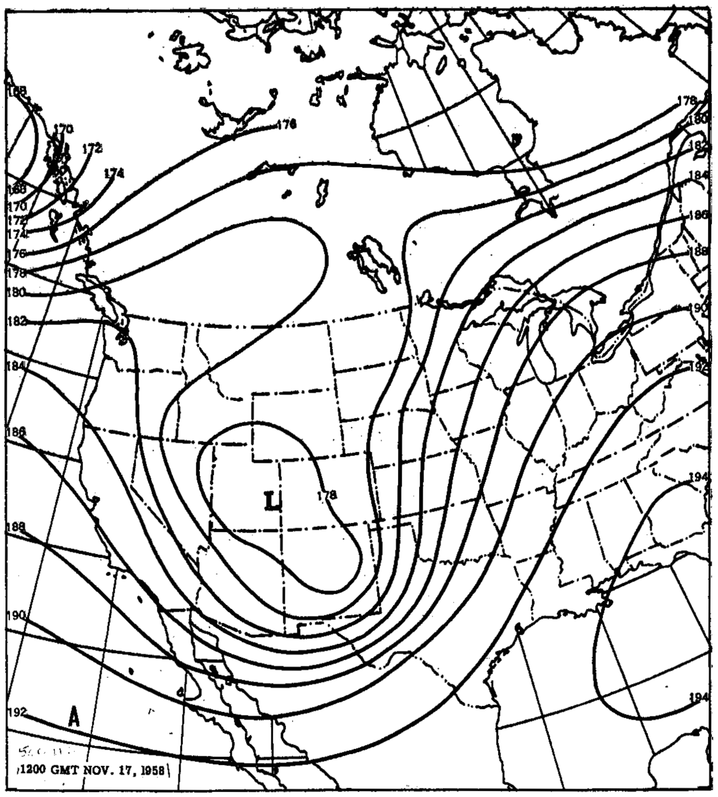


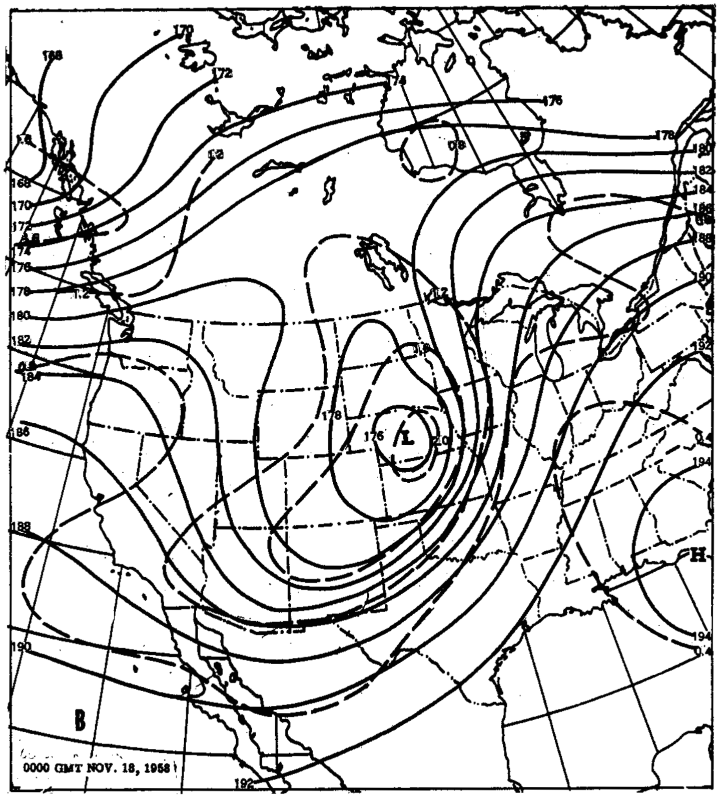
FIGURE 4.—1000-mb. contours (solid lines) and 1000–500-mb. thickness (dashed lines) for period of stage II, November 17–18, 1958. Shading shows current precipitation.

previous 48-hour period. A definite increase in vorticity was noted in the base of the trough. The jet stream reached its minimum latitude at roughly this time. The strong Gulf of Alaska ridge had weakened and moved to just off the Pacific Northwest coast, serving both to decrease the half-wave length and to increase the mean westerlies between it and the trough in southwestern United States. The thickness pattern and 1000-mb. frontal system changed in accordance with the 500-mb. developments, both having assumed a more north-south orientation in the area to the east of the 500-mb. trough. The two Low centers at 1000 mb. located in northeastern South Dakota and near El Paso, Tex., are identifiable with the centers in Wyoming and Nevada, respectively, 48 hours earlier, even though an examination of intermediate charts reveals continuity of movement during the 2 days is difficult to maintain. The measure of identification is the thickness ridge associated with the South Dakota center and the 500-mb. vorticity maximum associated with the El Paso center. Again, as in the previous 48 hours, there was comparatively little change in 1000-mb. vorticity although the change was definitely an increase.

In summary, Stage I can be characterized as follows: the gradual amplification over a 4-day period of the Gulf of Alaska upper trough as it progressed at a decelerated rate into western United States. This resulted in a major outbreak of cold air into southwestern United States. Throughout the 4 days the change in 1000-mb. vorticity associated with the 500-mb. trough was small.

In a broad sense the lower-level vorticity existing over the Northern Plains and southern Rockies at the end of the period can be looked upon as having gotten there from the northern Gulf of Alaska by translation.





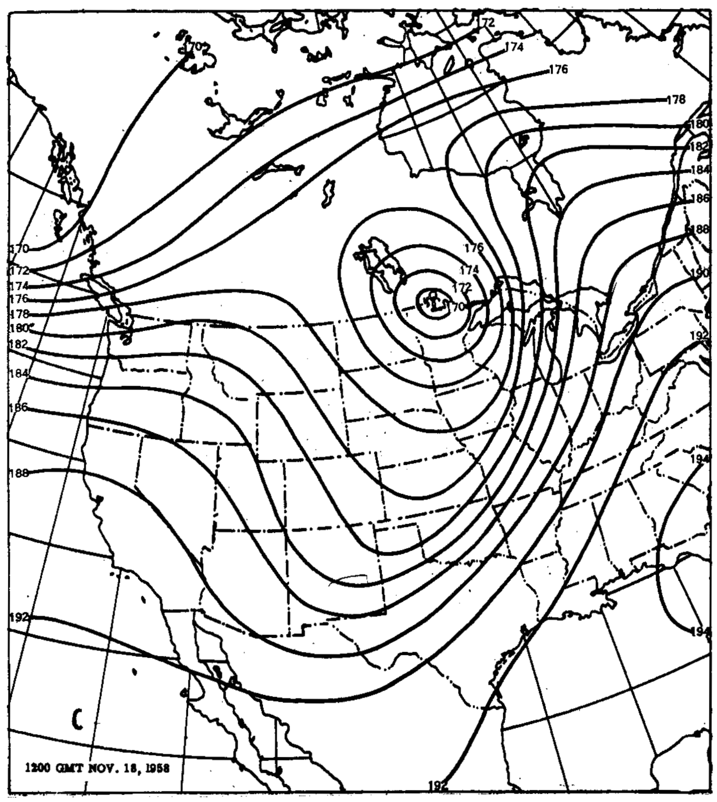


FIGURE 5.—500-mb. contours for times corresponding to figure 4. Absolute vorticity pattern (dashed lines, unit 10^{-4} sec^{-1}) is shown on (B).

3. STAGE II

Stage II began at 0000 GMT, November 17, and ended at 1200 GMT, November 18. Figures 3 and 4 for Stage II are similar in content to those for Stage I with the exceptions that, because JNWP computations of vorticity are made only once daily, vorticity isopleths are missing for 500-mb. charts at 1200 GMT, and the time interval between charts is 12 hours.

Absolute geostrophic vorticity (not shown to avoid confusion) was computed at 500 mb. for 12-hour periods beginning with 0000 GMT, November 17, and ending at 1200 GMT, November 18, to obtain continuity in the vorticity changes and also to establish a relationship between the JNWP computations of vorticity and geostrophic vorticity. As was to be expected, the geostrophic values were greater than the JNWP computations in regions of strong cyclonic curvature.

The situation at 1200 GMT, November 17, is shown in figures 4A and 5A. The upper trough in southwestern United States had accelerated in a northeastward direction, moving nearly as far in 12 hours as it had the previous 48 hours. The upper ridge along the west coast had continued to weaken and move eastward. At 1000 mb. the El Paso Low center had also accelerated and with little change in intensity moved to extreme southwestern Oklahoma. The frontal system extending from Iowa to northern Mexico was unusually strong, as can be seen from the thickness contours and the convergence of the 1000-mb. wind along the front. Surface temperature differences through the front in the vicinity of the Low were as much as 40° F. in 100 miles. Surface pressure tendencies at this time suggested the beginning of deepening for the Oklahoma Low. The South Dakota Low center had moved very slowly and was still associated with a pronounced thickness ridge.

During the next 24 hours (figs. 4B, 4C, and 5B, 5C) the changes at both upper and lower levels were large. The upper trough or vorticity maximum moved north-northeastward with little change in intensity until after 0000 GMT, November 18, when a marked increase in intensity occurred. The increase was coincident with the period of occlusion of the 1000-mb. Low center. The Oklahoma Low moved almost due north, deepening and changing in structure from a flat wave to a fully occluded storm. The major part of this change occurred in the 12-hour period from 1800 GMT, November 17, to 0600 GMT, November 18.

In summary, Stage II can be characterized as follows: the acceleration of the southwestern United States upper trough northeastward, which was associated with the rapid development of an intense storm over north-central United States. The net result at both the upper and lower levels was for a pronounced increase in the mean westerly wind component over the western half of the United States.

4. THE CYCLOGENESIS DURING STAGE II

Using certain approximations based on the vorticity equation, Sutcliffe [1] arrived at the following, now long familiar, expression for the relative divergence between two pressure levels:

$$f(\mathrm{div}_p\mathbf{V}-\mathrm{div}_p\mathbf{V}_0)=-\mathbf{V}_t\cdot\nabla_p(2\zeta_0+\zeta_t+f)$$

where the symbols have their usual meaning and subscripts 0 and t refer to the lower pressure level and the thermal wind between the two pressure levels, respectively.

Taking the two pressure levels at 500 and 1000 mb. and assuming zero divergence at 500 mb., the foregoing equation reduces to—

$$\mathrm{div}_p\mathbf{V}_0=\frac{1}{f}\mathbf{V}_t\cdot\nabla_p(2\zeta_0+\zeta_t+f)$$

which, assuming $\mathbf{V}_t\cdot\nabla f$ small in comparison with the other two terms on the right, relates the 1000-mb. divergence to the advection of the 1000-mb. vorticity and the thermal vorticity by the thermal wind. As pointed out by Sutcliffe, the second term on the right, the "thermal vorticity" effect, is the important one when considering the intensification of a Low center. It is large and contributes to intensification in regions where the thermal wind is strong and blows from high to low values of thermal vorticity. Since the change in thermal vorticity along the thermal wind is largely determined by changes in curvature, development is favored in regions where the curvature of the thickness contours changes rapidly from sharply cyclonic to sharply anticyclonic. It should also be noted that the term $\mathbf{V}_t\cdot\nabla_p\zeta_0$, which Sutcliffe calls the steering effect, normally balances or opposes the thermal vorticity effect.

Figure 6 shows in a qualitative manner the variation of the thermal vorticity effect at 12-hour intervals beginning with 0000 GMT, November 17. The magnitude of the effect is inversely proportional to the size of the quadrilaterals formed by the intersections of the thickness contours with the isopleths of thermal relative vorticity. The area under discussion will be that between the accelerating upper trough and the associated 1000-mb. Low center.

At 0000 GMT, November 17 (fig. 6A), the thermal vorticity effect was small and opposed by the steering effect. An increase occurred 12 hours later (fig. 6B), but the effect was still largely opposed by the steering effect. At 0000 GMT, November 18 (fig. 6C), when cyclogenesis was taking place in earnest, there was a further slight increase, but more significantly the area over which the effect was large expanded to include areas in which there was no opposition by the steering effect. During the succeeding 12 hours more or less of a balance between the thermal vorticity and steering effects returned (fig. 6D) and the Low center ceased deepening.

In the broadest sense, one can say the cyclogenesis was brought about by an increased deformation of the thickness contours. This increased deformation resulted when the cold air associated with the accelerating upper trough moved into juxtaposition with the nearly stationary thickness ridge over the Upper Mississippi Valley region. It is felt the prior existence of the thickness ridge was a necessary condition for the cyclogenesis or at least largely determined the area of most rapid development.

This analysis, based on the Sutcliffe development equation, of the cyclogenesis is admittedly a highly simplified one. It is essentially the same as attributing cyclogenesis to the superimposition of vorticity advection in the mid-troposphere over a slowly moving front at sea level (Petterssen [2]). From a forecasting point of view, its merit, if any, over Petterssen's is that it places emphasis upon the thickness contours, and more importantly the configuration of the thickness contours, which may or may not follow from the sea level frontal analysis, in advance of an accelerating upper trough.

5. SIMILAR STORMS DURING NOVEMBER SINCE 1945

A brief study of the Historical Weather Map series revealed the fact that since 1945 [1] there have been a total of 10 storms similar to the one studied here in the month of November alone, all occurring in the Central, North-Central, or Great Lakes regions of the United States. All 10 storms reached a minimum pressure over the United States of 985 mb. or lower with the exception of one. Including the storm this year then, since 1945 there has been an average of nearly one unusually intense storm a year. When considering the time and space limitations and also the intensity requirement for inclusion in the list, this is truly an amazing fact. It is almost as if the atmosphere announces the beginning of winter over central United States in November by a spectacular cyclogenesis. Following are the dates on which this announcement has been made:

[1] Study limited to years in which 500-mb. charts were available.

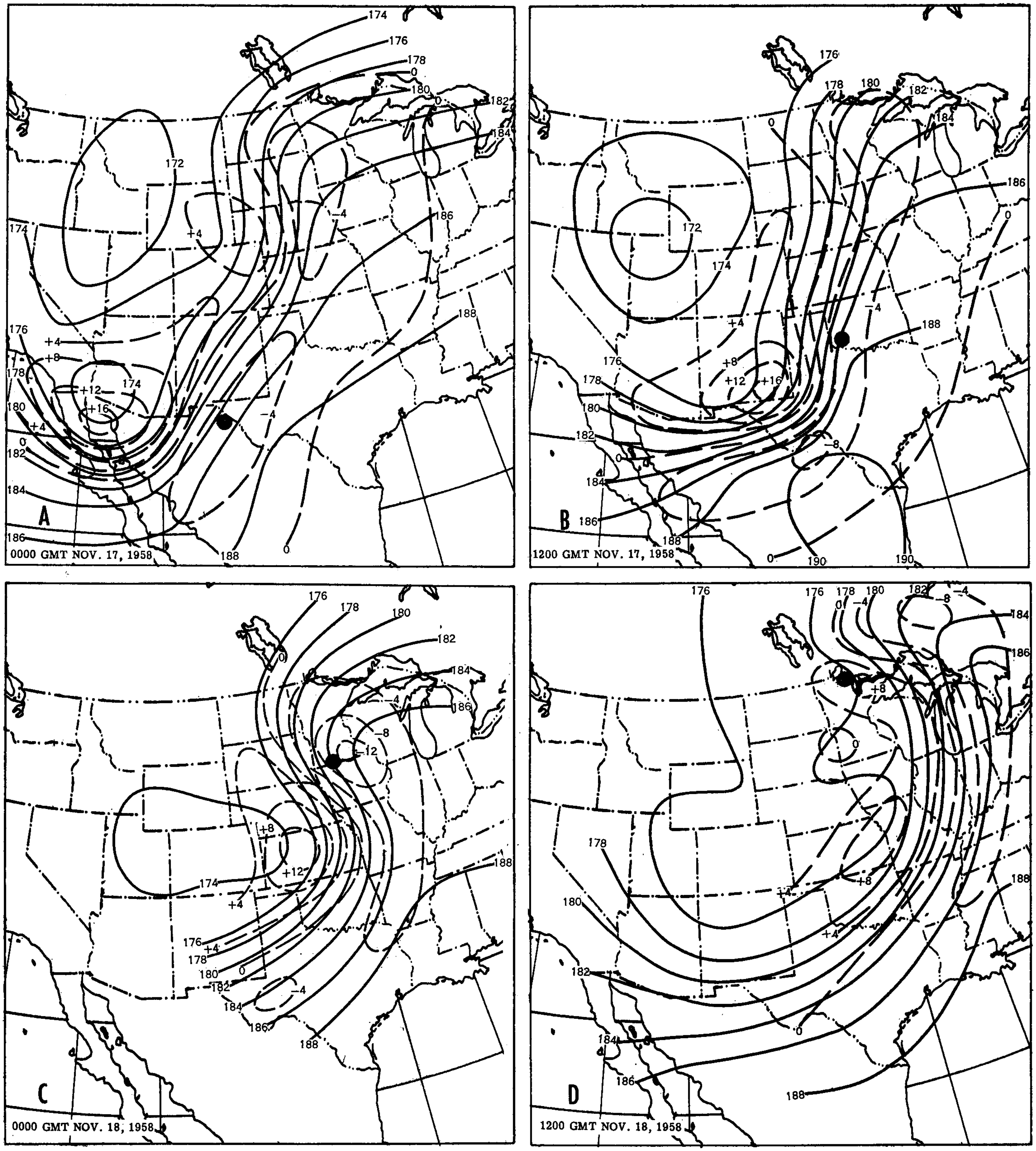


FIGURE 6.—Variations in Sutcliffe's thermal vorticity effect during Stage II. 1000–500-mb. thickness contours (solid lines, labeled in hundreds of feet) and the Laplacian of the thickness (dashed lines, relative units). Black dot indicates position of Low center.

November 13, 1945.
November 6–7, 1946.
November 22, 1946.
November 7–8, 1947.
November 5–6, 1948.
November 14, 1951.
November 25–26, 1952.
November 16–17, 1955.
November 21, 1956.
November 19, 1957.

All of these storms exhibited what can be termed two stages. The characteristics of the stages were similar to what has been described here, the primary difference being the difference in duration of Stages I and II. By way of

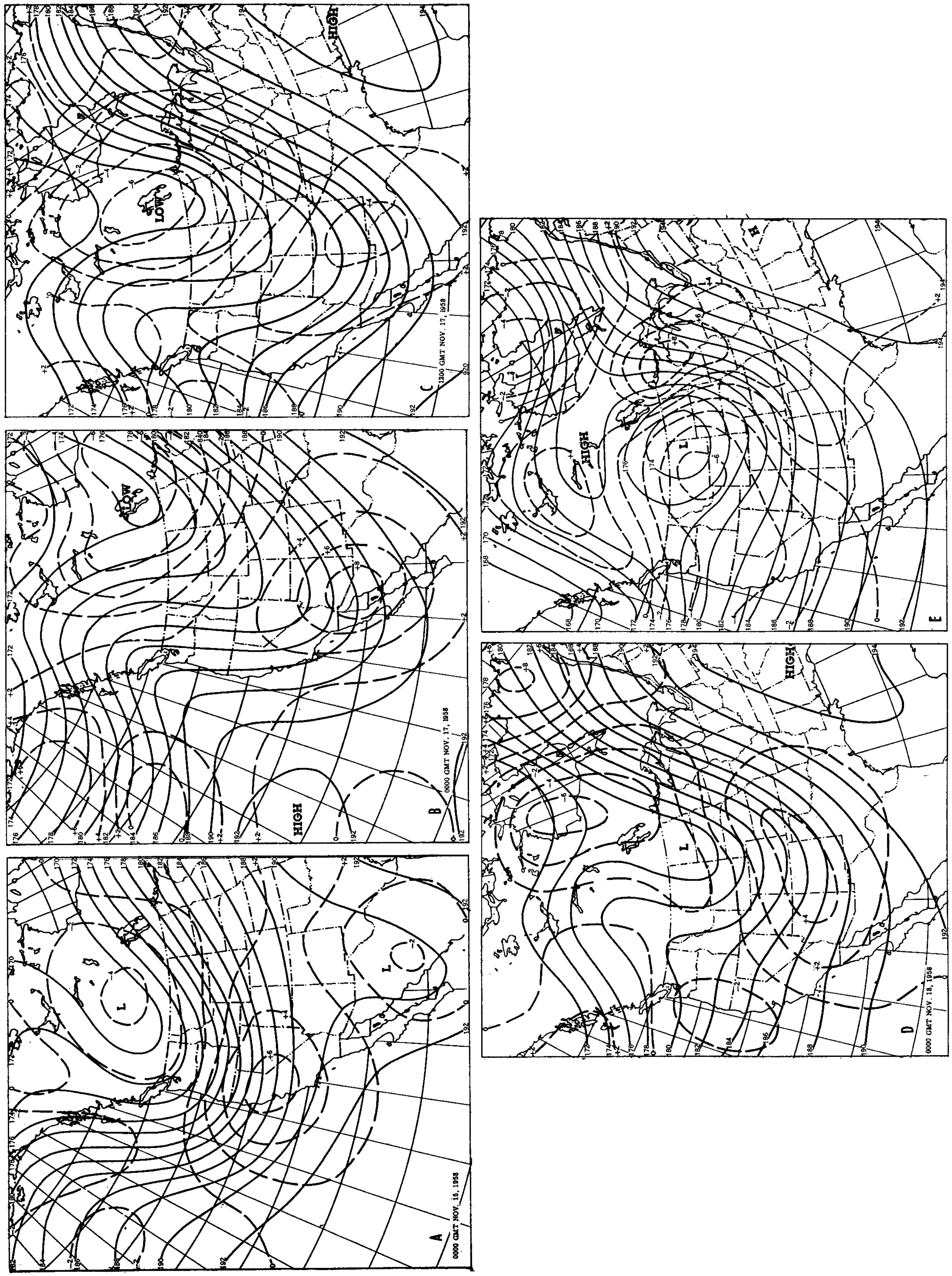


FIGURE 7.—48-hour barotropic 500-mb. JNWP prognostics (solid lines) for all times for which 500-mb. charts are shown in figures 3 and 5, with the exception of 0000 GMT, November 13. Dashed lines show error in hundreds of feet.

emphasis, all these storms were preceded by a period in which amplification and deceleration of an upper trough occurred while lower-level cyclogenesis was slight compared to that which followed when a trend to increasing upper westerlies set in.

The storm of November 6–7, 1946, which did not reach a minimum pressure of 985 mb., is listed because it represents a case in which the difference in characteristics between Stages I and II is extreme. An upper Low developed over New Mexico (see Palmén [3]) and remained *nearly stationary for a period of 3 days. During this* period the associated surface pattern was primarily anticyclonic. The upper Low eventually accelerated northeastward accompanied by the development of an intense surface storm.

6. USEFULNESS OF THE NWP 48-HOUR 500-MB. PROGNOSTIC TO THE FORECAST PROBLEM

According to the results of this study, the forecast problem may be divided into three parts. First, the growth of the upper trough in western United States had to be predicted. Second, the acceleration of the trough northeastward had to be accurately timed. Third, the favorable (for development) configuration of the thickness contours over north central United States had to be recognized or diagnosed.

Parts one and two of the problem have long been recognized by synoptic meteorologists with many years of forecasting experience in the Midwest. The U. S. Weather Bureau District Forecast Center at Kansas City, Mo., attempts to take these factors into account by certain objective rules applied to the 500-mb. level [4]. In spite of an awareness of the major points in the problem, meteorologists continue to have difficulty in presenting a forecast that has some degree of preciseness in time and space.

At this point we shall review the usefulness of the Numerical Weather Prediction 48-hour 500-mb. barotropic prognostic (hereafter called simply NWP forecast) to the solution of the forecast problem.

The NWP forecasts verifying at all times for which 500-mb. charts are presented in figures 3 and 5, with the exception of 0000 GMT, November 13, are shown in figure 7. Also included is the error in hundreds of feet.

First, a few general remarks concerning the errors. The barotropic model has been gradually improved to the point where it now seems, to those who are involved in the daily use of NWP forecasts, as if the remaining errors are largely caused by departures of the atmosphere from barotropic behavior. Most of this improvement has resulted from the following: (1) elimination of boundary problem errors through use of a hemispheric grid, (2) use of the so-called "balance equation" to obtain wind and vorticity at 500 mb. [5] which has eliminated the "blowup" or "spurious anticyclogenesis" problem, and (3) the stabilization of the very long atmospheric waves (Cressman [6]) which has done away with certain large-scale error patterns and greatly improved forecasts of 500-mb. height values.

Looking at the errors in NWP forecasts during this period, we see that positive errors were intimately associated with areas of cold-air advection and, to a lesser extent, negative errors with warm-air advection. Temperature advection is one common measure of baroclinicity. Note, especially, the positions of maximum positive and negative errors in figure 7B and compare with temperature advection patterns as indicated in figure 2C. During Stage I the position and sign of the errors were such as to result in a forecast of too little amplification. During the early part of Stage II the magnitude of the errors decreased but became large again at 1200 GMT, November 18, in the region of the cyclogenesis. Whereas the errors during Stage I did not affect the forecast accuracy of the upper trough position in western United States, at the end of Stage II the position and sign of the errors were such as to result in the trough being forecast slow at the latitude of the cyclogenesis.

In spite of the errors during this period, which were unusually large, a visual comparison of the NWP forecasts with the verifying charts reveals the NWP forecasts went a long way toward foretelling the sequence of events.[2] Of special interest are the forecasts during the transition from Stage I to Stage II; i. e., the change from increasing amplitude and deceleration to decreasing amplitude and acceleration. Comparing the forecast for 0000 GMT, November 15 (fig. 7A), with the one for 0000 GMT, November 17 (fig. 7B), in the area of southwestern United States, one can easily see the prediction of acceleration for the trough at the latitude of the jet stream. Whereas the NWP forecasts implied a displacement of the trough at the latitude of the jet stream of only 6° of longitude in the 48 hours between 0000 GMT, November 15, and 0000 GMT, November 17, the forecasts implied a displacement of 7° of longitude during the succeeding 12 hours (fig. 7C). The success of the forecast was undoubtedly related to the excellence with which the NWP forecasts handled the displacement and decrease in amplitude of the upstream ridge in the Eastern Pacific. (It should be added that all NWP forecasts of shorter time were in harmony with the foregoing.) Since the cyclogenesis in central United States was primarily dependent upon a forecast acceleration of the trough from southwestern United States, it might not be unreasonable to state that the NWP forecast, which by definition is incapable of predicting development, telegraphed the timing of this development 2 days in advance.

In summary, one is impressed with the following: that despite the highly baroclinic nature of the situation, the NWP barotropic forecasts told much about the sequence of events at 500 mb. and in turn at the surface. It seems as if the baroclinic effects throughout the period operated in the *framework* of a barotropic atmosphere. The baroclinic effects, even though large, acted to change only the *degree* of the barotropic developments and not the *substance*.

[2] This should be especially evident to meteorologists involved in producing forecasts during the period.

In view of the preceding paragraph, remarks by Rossby in 1949 [7] seem pertinent. Rossby stated, "Once a cold anticyclonic dome has been formed it may, through southward displacement and sinking, contribute materially to the intensification of the upper long-wave pattern and may lead to the formation of closed cyclonic centers aloft.[3] Nevertheless, several years of aerological experience indicate that the formation of such upper-level vortices is, to a considerable degree, predictable from the interaction between long waves aloft and from the general character of the flow pattern at these levels. We are thus led to the conclusion that the places where the formation of cold domes is initiated and where potential energy is released ultimately are determined by the upper long-wave pattern."

ACKNOWLEDGMENTS

The writers take this opportunity to thank the members of the Daily Map Unit of the Weather Bureau for drafting of the figures.

[3] This process appears to parallel closely the course of events during Stage I.

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